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EXPERIMENTAL VERIFICATION OF A DOUBLE-DEAD-TIME MODEL DESCRIBING CHUGGING IN LIQUID-BIPROPELLANT ROCKET ENGINES

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TECHNICAL PAPER proposed for presentation at Fourth Combustion Conference sponsored by the Interagency Chemical Rocket Propulsion Group
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ABSTRACT

Stability limits were determined, experimentally, for a 2-inch diameter rocket engine. Liquid oxygen and gaseous hydrogen were the propellants. Boundaries were determined for two engine configurations: a chamber pressure of 650 psia, contraction ratio of 16.8, and a chamber pressure of 300 psia, contraction ratio of 8.4. The oxidant-fuel weight ratio was maintained at 5.0 with a characteristic length of approximately 95 inches.

For comparison with experimental data, stability boundaries were generated on the analog computer, using the chugging model proposed by the authors and values of combustion delay, as determined from an existing vaporization model. Experimental and computer data agreed with regard to observed chugging frequencies and boundary shape. Discrepancies in boundary location (required injector pressure drops) were attributed to a high combustion noise level caused by the injection system used. The proposed model is further supported by noting observations made on several large-scale engines.

INTRODUCTION

Low frequency instabilities in liquid-propellant rocket engines, commonly referred to as chugging, have been the subject of many analyses during the past two decades (1, 2, 3). The purpose of this investigation was to verify, experimentally, the chugging model advanced by the authors (4). A comparison of the proposed model and the commonly used, single-delay model is made in figure 1. In both cases, a completely decoupled feed-system is assumed. That is, injector pressures are non-varying due to high dome compliances.

For the single-delay model, the injector flow rates are acted upon by a single delay, usually assumed to be made up of the governing vaporization time, mixing and reaction times. For an oxidizer-limited system, this would be valid for the case of high fuel injector pressure drop (5, 6).

To analyze chugging over a wide range of operation and/or when one of the propellants is introduced as a gas, each propellant must be assumed to be acted upon by a discrete delay, made up of its vaporization time (if any) and the mixing and reaction times, common to both propellants.

Figure 2 shows typical stability boundaries for both models, plotted as ratios of injector pressure drop to chamber pressure. For the case shown, the fuel is introduced as a gas ($\tau_{vf} = 0$). The single-delay boundary has the typical, hyperbolic shape with the entire boundary corresponding to one chugging frequency. The double-delay boundary has two distinct characteristics: a reversed-slope at high fuel ΔP, and a discontinuity in the observed frequency along the boundary. Figure 3 contains a Nyquist stability plot for the shaded operating point in figure 2. Encirclements of the -1 point correspond to an unstable condition. As indicated, this point would be stable at the lower frequency but unstable at the higher (435 Hz).

APPARATUS

Figure 4 illustrates the injector design used in this study. High fuel injector compliance was provided by closely-coupling a large plenum to the injector cavity. For the LOX injector, the compliance had to be increased mechanically. A thin Inconel diaphragm, supported by gas pressure and the perforated plate, was designed to attenuate pressure oscillations during chugging. Careful design was required to prevent coupling with the inertance of the plate holes in the frequency range of interest. Variations in fuel and oxidizer injector ΔP's were accomplished by changing Rigimesh thickness and orifice diameter, respectively. Copper-chambers, 2 inches in diameter, with lengths ranging from 2.1 to 12.5 inches were used. Water-cooled nozzles, with contraction ratios of 8.4 and 16.8 were run at nominal chamber pressures of 300 and 650 psia, respectively. The LOX flow rate was nominally .55 pound per second at an O/F of 5.0.

PROCEDURE

To aid in the analysis of the system and to facilitate the planning of experiments, cold-flow tests were conducted on both propellant systems. A minimum LOX ΔP of 60 psia was attained at the rated flow rate with no orifice in the system. The pressure-drop and flow rate were related by the familiar square-law. The hydrogen cold-flow and hot-run injector data was matched by assuming constant temperature and a linear pressure gradient through the Rigimesh. A modified square-law was used with the average density computed from the sum of upstream and downstream pressure.

Because of the relative ease in changing the orifice between runs, boundaries were determined by cutting horizontally across the $\Delta P/P$ map. Orifice size was increased until a transition from stable to unstable operation was noted. System operation was open-loop with iterations in supply pressures required to achieve the desired flow conditions.

EXPERIMENTAL RESULTS

For the engine considered, the transition from "stable" to "unstable" operation was a gradual one with seemingly random fluctuations in the amplitude of chamber pressure oscillations. Due to this randomness, a stability criterion, based on a time-average over a set portion of the run, had to be chosen. A limit on the allowable RMS value of the chamber pressure oscillation was set at 10 percent of the mean pressure. Spectrum analysis showed that, in all cases, the resultant oscillation could be considered as having two dominant frequency components. The recording of the chamber pressure oscillations were filtered and analyzed at those frequencies.

The resultant boundary for the high chamber pressure case is shown in figure 5, with the determining data points shown. Frequencies in both the 70 and 170 Hz ranges were observed. At an oxidizer $\Delta P/P$ of 0.4, a reduction in fuel $\Delta P/P$ from 0.4 to 0.2 stabilizes the engine.

Figure 6 contains the resultant boundary for the low chamber pressure case. A bending back of the boundary occurs at a fuel $\Delta P/P$ of about 0.3. Possible causes being investigated are: the effect of reduced fuel velocity on oxidizer drop size and vaporization rate, and a possible coupling effect from the feed system. However, both characteristics of the double-dead-time model were observed with chugging in the 40 and 110 Hz ranges.

ANALYSIS

For comparison with the experimental data, stability boundaries were generated on the analog computer using the system equations (4), and LOX vaporization times, computed using the methods of Priem and Heidmann (7). Mean oxidizer drop sizes were computed from combustion efficiency-chamber length data obtained at a chamber pressure of 300 psia. Lengths required to vaporize 50 percent of the oxidizer mass were computed to be: 5.5 inches at a chamber pressure of 300 psia with an injection velocity of 735 in/sec, and 3.6 inches at a chamber pressure of 650 psia with an injection velocity of 762 in/sec. Assuming that the average droplet velocity over this length is the injection velocity, the vaporization time (time to vaporize 50 percent) was computed to be 7.5 ms at 300 psia, and 4.7 ms at 650 psia. Based on the observed chugging frequencies at high fuel $\Delta P/P$'s, mixing times were determined from $\tau_{total} - \tau_{vo}$, where τ_{total} is the total delay required to satisfy the phase requirement for neutral stability. The resultant values were 3.8 ms at 300 psia, and 2.0 ms at 650 psia. Final adjustments of all values of delay were made on the computer to match the observed frequencies for both ranges of chugging.

In an attempt to duplicate the boundary position and chamber pressure waveshape, white noise was superimposed on the simulated products of combustion at P_c = 650 psia. The required noise level was determined by matching the observed ratio of RMS to mean chamber pressure amplitudes at "stable" values of injector $\Delta P/P$'s. A noise level, resulting in 7 percent oscillations, was determined.

A comparison of the experimental and computer boundaries for both configurations are given in figures 7 and 8. For the high chamber pressure case, deviations occur at low values of fuel $\Delta P/P$ creating some doubt as to the validity of the selected stability criterion at values of $\Delta P/P$ below 0.1. The results at the low chamber pressure indicate the possibility that the absolute noise level is a function of injector configuration rather than chamber pressure.

SUMMARY OF RESULTS

Experimental testing and analysis, reported herein, yielded the following results:

1. The validity of the double-dead-time model has been demonstrated. Both configurations exhibited the characteristic behavior of the proposed model.

2. Values of LOX vaporization time required to match the observed chugging frequencies, were within 7 percent of those predicted by Priem and Heidmann.

3. Mixing times must be inferred from the observed frequencies and vaporization times.

4. The classification of data as stable or unstable, together with the resulting boundary position, were influenced by the high combustion noise level caused by the coarse injection technique used.

CONCLUDING REMARKS

Preliminary data from tests being conducted on a seven-element, concentric tube injector with a contraction ratio of 1.9, indicate a sharp transition from stable to diverging, unstable operation at injector ΔP's very close to the theoretical values. The observed frequencies indicate a LOX vaporization time close to that predicted with a more typical mixing time of 0.2 to 0.4 ms.

Analysis of chugging data obtained on various full-scale engines has emphasized the need to treat the combustion delays separately. M-1 chugging data has been explained using the double-dead-time model, Priem's vaporization times, and mixing times around 0.2 ms. Data from the J-2 engine (8) indicated the possibility of stabilization by decreasing the fuel $\Delta P/P$. Recent chugging experience on the LEM Ascent Engine indicates a "second-mode" instability with delays consistent with predictions made by Priem and Heidmann.

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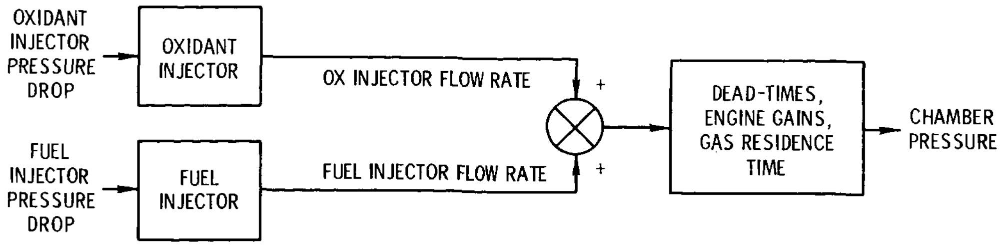
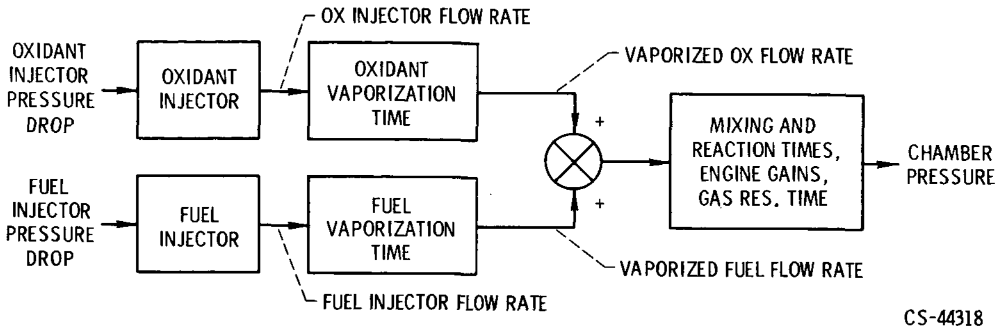
COMPARISON OF STABILITY LIMIT MODELS FOR BI-PROPELLANT ROCKET ENGINES



(A) SINGLE DEAD-TIME MODEL.



(B) DOUBLE DEAD-TIME MODEL.

Figure 1

TYPICAL STABILITY BOUNDARY FOR DOUBLE DEAD-TIME MODEL

$\tau_{vf} = 0,\ \tau_{vo} = 1.75$ ms, $\tau_m = 1.0$ ms, $\theta_g = 0.7$ ms

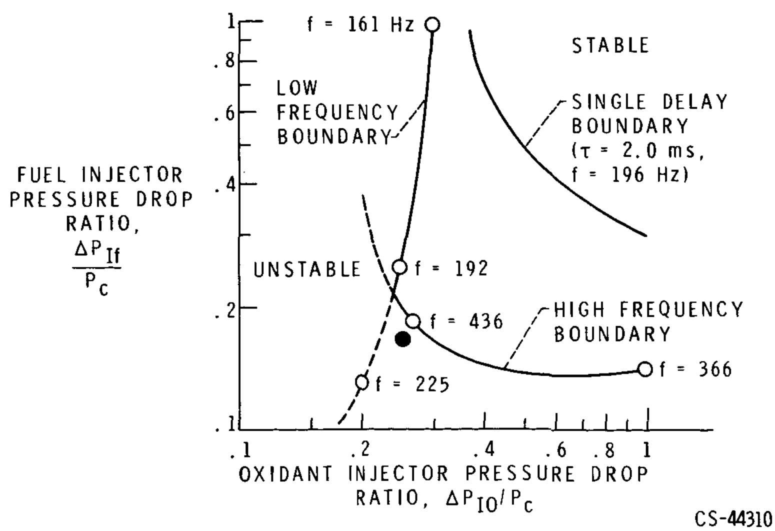


Figure 2

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TYPICAL FREQUENCY RESPONSE BEHAVIOR FOR DOUBLE DEAD-TIME MODEL

$\tau_{vf} = 0$, $\tau_{vo} = 1.75$ ms, $\tau_m = 1.0$ ms, $\theta_g = 0.7$ ms,
$\Delta P_{IO}/P_c = 0.257$, $\Delta P_{If}/P_c = 0.168$

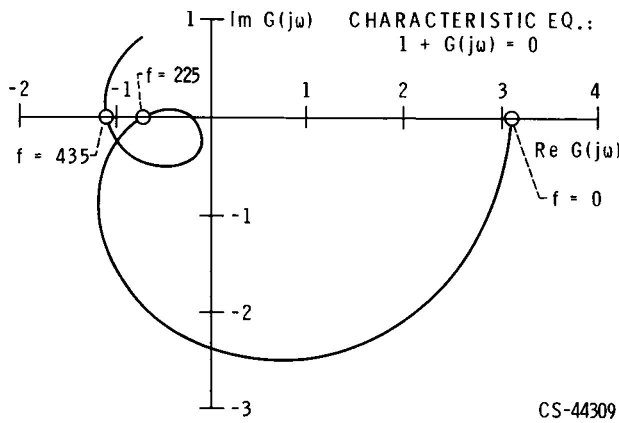

Figure 3

H-O CHUGGING INJECTOR CUT-AWAY

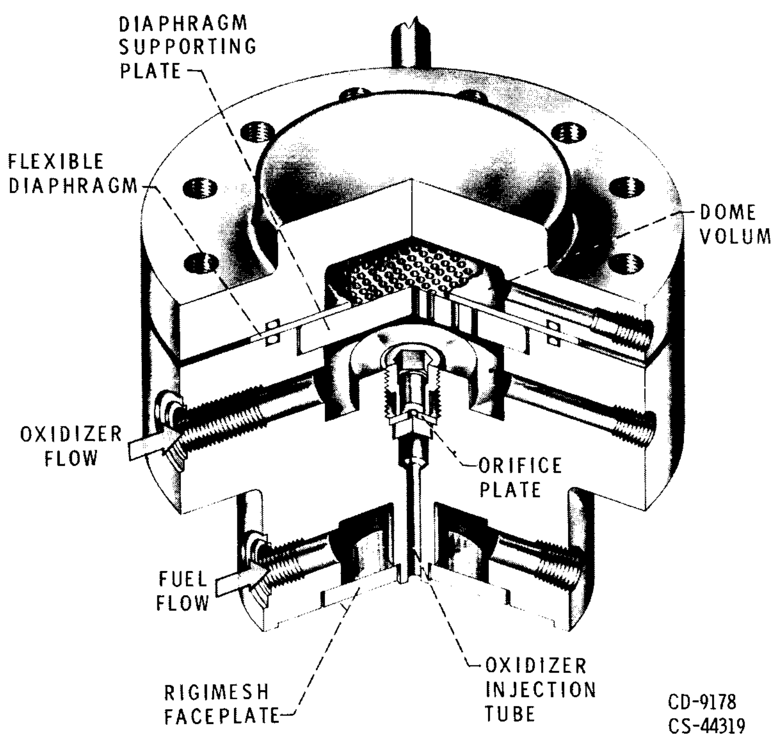

Figure 4

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EXPERIMENTALLY DETERMINED STABILITY BOUNDARY

P_C = 650 PSIA, O/F = 5.0, $\dot{w}_O$ = 0.55 LB/SEC, L* = 91.0 IN.

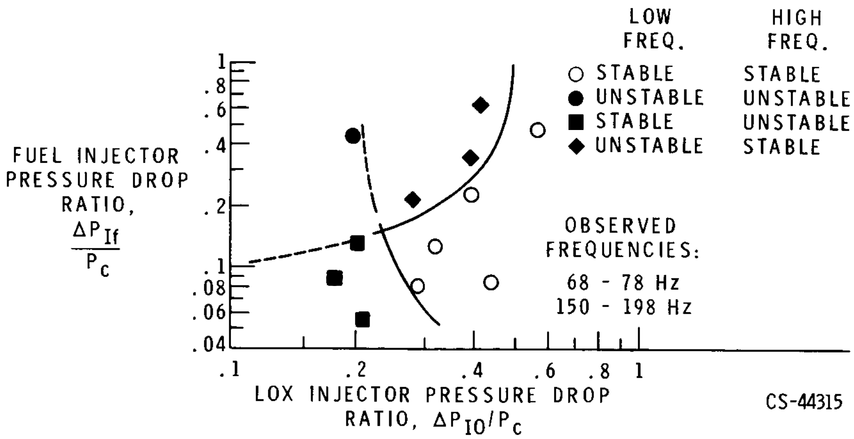

Figure 5

EXPERIMENTALLY DETERMINED STABILITY BOUNDARY

P_C = 300 PSIA, O/F = 5.0, $\dot{w}_O$ = 0.55 LB/SEC, L* = 95.5 IN.

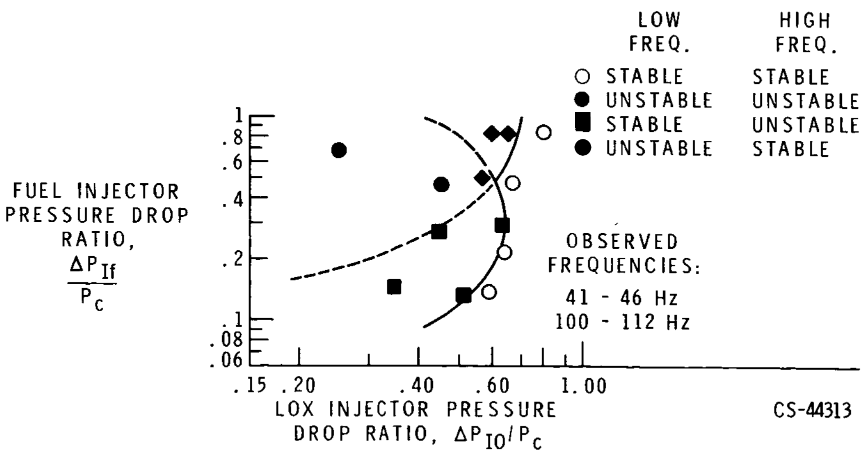

Figure 6

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COMPARISON OF EXPERIMENTAL AND SIMULATION STABILITY BOUNDARIES

P_c = 650 PSIA, τ_{vf} = 0, τ_{vo} = 4.4 ms, τ_m = 2.2 ms, θ_g = 2.0 ms,
7% NOISE LEVEL

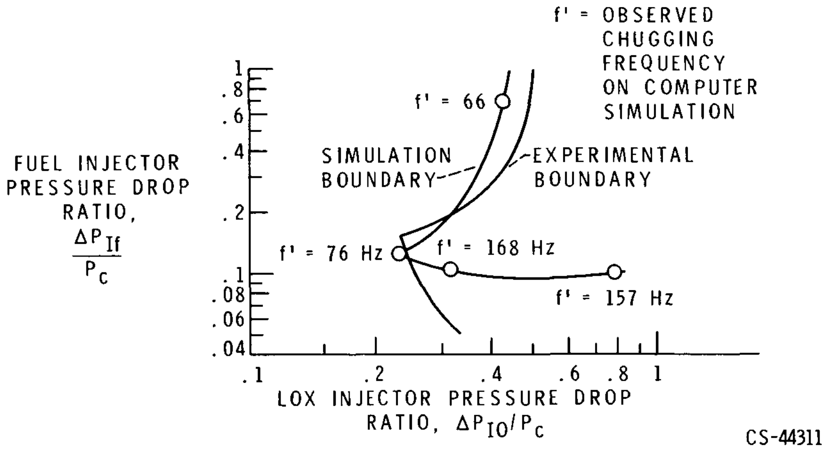

Figure 7

COMPARISONS OF EXPERIMENTAL AND SIMULATION STABILITY BOUNDARIES

P_c = 300 PSIA, τ_{vf} = 0, τ_{vo} = 8.0 ms, τ_m = 4.0 ms,
θ_g = 2.1 ms, 7% NOISE LEVEL

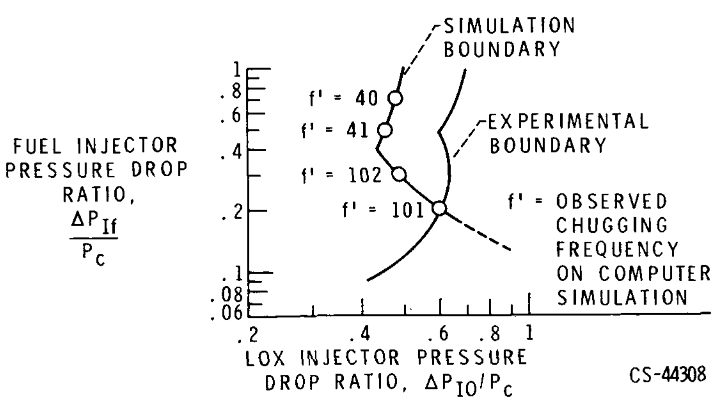

Figure 8

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